

Ground-State Masses and Magnetic Moments of Heavy Baryons

Zahra Ghalenovi^{a,b}, Ali Akbar Rajabi^b, Si-xue Qin^a, Dirk. H. Rischke^{a,c}

^aInstitute for Theoretical Physics, Johann Wolfgang Goethe University, Frankfurt am Main, Germany

^bPhysics Department, Shahrood University of Technology, Shahrood, Iran

^cFrankfurt Institute for Advanced Studies, Frankfurt am Main, Germany

Abstract

In this work we study single, double, and triple heavy-flavor baryons using the hypercentral approach in the framework of the non-relativistic quark model. Considering two different confining potentials and an improved form of the hyperfine interaction, we calculate the ground-state masses of heavy baryons and also the ground-state magnetic moments of single charm and beauty baryons with $J^P = 3/2^+$. The obtained results are in good agreement with experimental data and those of other works.

Key words: Heavy baryons, hypercentral approach, confining potential, non-relativistic quark model.

PACS Nos.: 14.20.Mr, 14.2.Lq, 12.39.Pn

1 Introduction

The properties of heavy-flavor baryons have recently received much attention, both experimentally and theoretically [1, 4, 2, 3]. The investigation of the properties of such hadrons is not only important to understand the dynamics of quantum chromodynamics (QCD) at hadronic energy scales, but also interesting in view of the recent progress in studying heavy-flavor hadrons by different experimental groups like BaBar, BELLE, BESIII, CLEO, and SELEX. Different methods based on the constituent quark model (CQM) have been used to investigate heavy-flavor baryons. Ebert et al. studied heavy baryons in the quark-diquark model in the relativistic limit [5]. Reference [4] investigated heavy-flavor baryons by using the Bethe-Salpeter equation in the heavy-quark limit and calculated the Isgur-Wise function. Albertus et al. evaluated different properties of single heavy-flavor baryons using heavy-quark symmetry in the non-relativistic quark model [6]. Flynn et al. studied charmed baryons and spin-splittings in quenched lattice QCD [7]. Faessler et al. considered ground-state magnetic moments of heavy baryons in the relativistic quark model using heavy-hadron chiral perturbation theory [8]. Patel et al. used the non-relativistic quark model with a hypercentral Coulomb plus linear potential and obtained masses and magnetic moments of heavy-flavor baryons [9, 10].

In the present work we calculate the ground-state masses and magnetic moments of heavy baryons in the hypercentral approach [11, 12, 13, 14, 15, 16, 17, 18, 19]. We study the three-body problem, particularly the baryons containing one, two, and three charm (beauty) quarks. The potential is assumed to be a combination of a long-range confinement part and a short-range potential which is a Coulombic one, depending on the color charge.

The solution of a three-body problem in three spatial dimensions is rather difficult. Here, we employ the hypercentral approach where the Schrödinger equation of the three-body system depends only on a single variable. We solve this one-dimensional Schrödinger equation numerically. We also introduce a non-confining interquark potential, namely a spin-isospin dependent part, as hyperfine interaction. We study the baryonic systems using two types of potentials. First, we introduce the Cornell potential, $bx - c/x$, as confining potential between quarks and obtain the masses of heavy baryons. Second, we add a harmonic oscillator term to the confining potential and then compare the obtained baryon masses to the results without this term, and also to those of other works. The obtained masses and magnetic moments are close to experimental data and other theoretical predictions.

This paper is organized as follows. In Sec. 2 we introduce the interquark potential. In Sec. 3 we simplify the three-body problem using the hypercentral approach. We present our method to obtain masses and magnetic moments of baryons in Sec. 4. Numerical results are shown and compared to those of other works in Sec. 5. Finally, a summary is given in Sec. 6.

2 Interaction Potential

In principle, the potential between quarks could be of any confining form (e.g. linear, logarithmic, power law, etc.). The interquark potential usually contains a linear part which describes confinement in QCD and is supplemented by a Coulomb term which may be attributed to one-gluon exchange. The Coulomb term alone is not sufficient because it would allow ionization of quarks from the system. As a first case (in the following termed “case I”), we consider the Cornell potential [20, 21]:

$$V(x) = bx - \frac{c}{x}, \quad (1)$$

where x is the relative coordinate of the quark pair, and b, c are constants. In many practical applications a harmonic oscillator (h.o.) potential yields spectra not much different from those for Eq. (1) [20]. Therefore, as a second case (termed “case II”) we also consider a potential which is a combination of Eq. (1) and the h.o. potential which has the form ax^2 :

$$V(x) = ax^2 + bx - \frac{c}{x}, \quad (2)$$

where a is another constant. In addition, we introduce a spin- and isospin-dependent potential as hyperfine interaction for the baryons. This combination of potentials yields spectra which are very close to the experimental results and other theoretical predictions.

The non-confining spin-spin interaction potential is proportional to a δ -function which is an illegal operator term [22]. We modify it to a Gaussian function of the relative distance of the quark pair,

$$H_S = A_S \frac{\vec{s}_1 \cdot \vec{s}_2}{(\sqrt{\pi}\sigma_S)^3} \exp\left(-\frac{x^2}{\sigma_S^2}\right), \quad (3)$$

where s_i is the spin operator of the i^{th} quark ($\vec{s}_i = \vec{\sigma}_i/2$, with $\vec{\sigma}_i$ being the vector of Pauli matrices) and A_S and σ_S are constants.

Other spin-, as well as isospin-dependent interaction potentials can arise from quark-exchange interactions. We conclude that two additional terms should be added to the Hamiltonian for quark pairs which result in hyperfine interactions similar to Eq. (3). The first one depends on isospin only and has the form [22, 23]:

$$H_I = A_I \frac{\vec{t}_1 \cdot \vec{t}_2}{(\sqrt{\pi}\sigma_I)^3} \exp\left(-\frac{x^2}{\sigma_I^2}\right), \quad (4)$$

where t_i is the isospin operator of the i^{th} quarks, and A_I and σ_I are constants. The second one is a spin-isospin interaction given by [22, 23]:

$$H_{SI} = A_{SI} \frac{(\vec{s}_1 \cdot \vec{s}_2)(\vec{t}_1 \cdot \vec{t}_2)}{(\sqrt{\pi}\sigma_{SI})^3} \exp\left(-\frac{x^2}{\sigma_{SI}^2}\right), \quad (5)$$

where s_i and t_i are the spin and isospin operators of the i^{th} quark, respectively, and A_{SI} and σ_{SI} are constants. Then, from Eqs. (3-5) the hyperfine interaction (a non-confining potential) is given by

$$H_{int}(x) = H_S(x) + H_I(x) + H_{SI}(x). \quad (6)$$

The parameters of the hyperfine interaction (6) are given in Table 1.

Table 1. Constituent quark masses and hyperfine - potential parameters used in cases I and II [11, 25].

parameter	value
m_u	330 MeV
m_d	335 MeV
m_s	469 MeV
m_c	1600 MeV
m_b	4980 MeV
σ_S	2.87 fm
A_S	67.4 fm ²
σ_{SI}	2.31 fm
A_{SI}	-106.2 fm ²
σ_I	3.45 fm
A_I	51.7 fm ²

3 The Hypercentral Approach

In the quark model, a baryon is a three-body bound state made of quarks. The mathematical description of a three-body system is more complicated than that of a two-body system. Several methods have been used by different authors to solve three-body problems [17, 18, 19, 22, 23, 24, 25, 26].

In order to describe the baryon as a bound state of three constituent quarks, we define the configuration of three particles by two Jacobi coordinates ρ and λ as

$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2), \quad \vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3), \quad (7)$$

such that

$$m_\rho = \frac{2m_1m_2}{m_1+m_2}, \quad m_\lambda = \frac{3m_3(m_1+m_2)}{2(m_1+m_2+m_3)}. \quad (8)$$

Here m_1 , m_2 , and m_3 are the constituent quark masses. Instead of ρ and λ , one can introduce hyperspherical coordinates which are given by the angles $\Omega_\rho = (\theta_\rho, \phi_\rho)$ and $\Omega_\lambda = (\theta_\lambda, \varphi_\lambda)$, respectively, together with the hyperradius x and the hyperangle ζ , defined by

$$x = \sqrt{\vec{\rho}^2 + \vec{\lambda}^2}, \quad \zeta = \arctan\left(\frac{\rho}{\lambda}\right). \quad (9)$$

Therefore, the Hamiltonian will be

$$H = \frac{P_\rho^2}{2m_\rho} + \frac{P_\lambda^2}{2m_\lambda} + V(\rho, \lambda) = \frac{P^2}{2m} + V(x). \quad (10)$$

In the hypercentral constituent quark model (hCQM), the quark potential, V , is assumed to depend only on the hyperradius x . Therefore, in the three-quark wave function one can factor out the hyperangular part which is given by hyperspherical harmonics. The remaining hyperradial part of the wave function is determined by the hypercentral Schrödinger equation

$$\left[\frac{d^2}{dx^2} + \frac{5}{x} \frac{d}{dx} - \frac{\gamma(\gamma+4)}{x^2} \right] \psi_\gamma(x) = -2m[E_\gamma - V(x)]\psi_\gamma(x), \quad (11)$$

where $\psi_\gamma(x)$, E_γ , and γ are the hyperradial part of the wave function, the energy eigenvalues, and the grand angular quantum number, respectively. The latter is given by $\gamma = 2\nu + l_\rho + l_\lambda$ where l_ρ

and l_λ are the angular momenta associated with the ρ and λ variables and ν is a non-negative integer number. The quantity m in Eqs. (10,11) is the reduced mass,

$$m = \frac{2m_\rho m_\lambda}{m_\rho + m_\lambda} . \quad (12)$$

We use the transformation

$$\psi_\gamma(x) = x^{-5/2} \phi_\gamma(x) \quad (13)$$

to bring Eq. (11) into the form

$$\left[\phi_\gamma''(x) - \frac{(2\gamma+3)(2\gamma+5)}{4x^2} \right] \phi_\gamma(x) = -2m[E_\gamma - V(x)] \phi_\gamma(x) . \quad (14)$$

Substituting the potentials (1) and (2) into Eq. (11) we obtain the following equations:

- (I) In case I we only consider the Cornell potential (1) as confining interaction. Using the hyperradial approximation used in Ref. [11], the Schrödinger equation for the baryons is given as

$$\phi_\gamma''(x) + 2\mu \left[-bx + \frac{c}{x} - \frac{(2\gamma+3)(2\gamma+5)}{8\mu x^2} \right] \phi_\gamma(x) = -2\mu E_\gamma \phi_\gamma(x) , \quad (15)$$

where $\mu = m$. As in Ref. [11], in the following we shall consider μ as a free parameter which is fitted to the baryon spectrum.

- (II) In case II, we add the h.o. term to the confining interaction. Then, using the potential (2) and substituting it into Eq. (14) we obtain the following equation:

$$\phi_\gamma''(x) + \left[-a_1 x^2 - b_1 x + \frac{c_1}{x} - \frac{(2\gamma+3)(2\gamma+5)}{4x^2} \right] \phi_\gamma(x) = -\varepsilon_\gamma \phi_\gamma(x) , \quad (16)$$

where

$$\varepsilon_\gamma = 2mE_\gamma , \quad a_1 = 2ma , \quad b_1 = 2mb , \quad c_1 = 2mc . \quad (17)$$

4 Heavy Baryon Masses and Magnetic Moments

We take the non-confining potential H_{int} , Eq. (6), as a perturbation of the energy eigenvalues obtained by solving Eqs. (15,16). To first order in perturbation theory, the correction can be computed using the unperturbed wave function for the ground state,

$$\langle H_{int} \rangle = \frac{\int \psi_0 H_{int} \psi_0 x^5 dx d\Omega_\rho d\Omega_\lambda}{\int \psi_0 \psi_0 x^5 dx d\Omega_\rho d\Omega_\lambda} . \quad (18)$$

Note that in Eqs. (3-5) the spin-isospin dependent interaction potentials of a two-quark system are actually functions of the relative distance between the quarks. In the hypercentral approach, however, we take the same form for these potentials, but replace the relative distance by the hyperradius x which is the average relative distance between the three quarks. We believe that this is a reasonable approximation, at least for quarks with the same mass. The spin-spin term $\vec{s}_1 \cdot \vec{s}_2$ in Eq. (3) is replaced by the average of $\sum_{i < j} \vec{s}_i \cdot \vec{s}_j$, and similarly for Eqs. (4,5).

The mass of the baryon is then obtained as the sum of the masses of the constituent quarks, the ground-state energy eigenvalue E_0 , and $\langle H_{int} \rangle$,

$$M_B = m_1 + m_2 + m_3 + E_0 + \langle H_{int} \rangle , \quad (19)$$

where $E_0 + \langle H_{int} \rangle$ depends on the type of confining interaction used. The effective quark mass is defined as

$$m_i^{eff} = m_i \left(1 + \frac{E_0 + \langle H_{int} \rangle}{\sum_i m_i} \right), \quad (20)$$

such that the mass of the baryon is

$$M_B = \sum_i m_i^{eff}. \quad (21)$$

The physical interpretation of the effective quark mass (20) is that, within a baryon, the mass of a quark may get modified due to its interactions with the other quarks.

In the quark model, the magnetic moment of the baryon is obtained as [9, 24]

$$\mu_B = \langle \phi_{sf} | M_z | \phi_{sf} \rangle, \quad (22)$$

where $|\phi_{sf}\rangle$ represents the spin-flavor wave function of the respective baryonic state and

$$\vec{M} = \sum_i \frac{g e_i \vec{s}_i}{2m_i^{eff}}. \quad (23)$$

Here, $g = 2$ is the spin g -factor, e_i is the electric charge, and \vec{s}_i the spin of the i^{th} quark.

5 Discussion

In Refs. [23, 25] heavy-flavor baryons were studied in the hypercentral approach with the confining interaction (2) and the hyperfine interactions (3-5). The Schrödinger equation was solved analytically to obtain masses of heavy-flavor baryons. In Ref. [11] heavy-flavor baryons were also studied in the hypercentral approach, but with the confining interaction (1) and the hyperfine interactions (3-5). The Schrödinger equation was solved using a variational method to obtain masses of single, double, and triple heavy-flavor baryons. Patel et al. used the non-relativistic quark model with hypercentral Coulomb plus linear potential [9, 24] and Coulomb plus harmonic oscillator potential [26] and obtained heavy-flavor baryon masses.

Table 2. The confining potential parameters used in case I and II [11, 25].

	parameter	value
caseI	b	1.61 fm^{-2}
	c	4.59
caseII	a	0.73 fm^{-3}
	b	0.81 fm^{-2}
	c	2.12

In the present work we use the same potentials and the hypercentral approach, but we solve the Schrödinger equation numerically. We study baryonic systems using the confining interactions (1) and (2), respectively. The quark masses and potential parameters used in both case I and II are obtained from our corresponding works [11] and [25], respectively, and are listed in Table 1. The confining potential parameters for the two cases are listed in Table 2. In case I, the parameter μ of Eq. (15) is obtained by fitting the experimental mass of the \sum_c^{++} baryon (resulting in $\mu = 0.844 \text{ fm}^{-1}$). Using μ as a fit parameter instead of identifying it with the reduced mass m allows to make an accurate comparison between the results of our present work and previous results [11].

In Tables 3-8 the results for the masses and magnetic moments are presented and compared with other works [24, 25, 26, 27, 28, 29, 30, 29] and experimental data [31, 32, 33, 34, 35]. From Tables 3-8

Table 3. Single charm baryon masses (masses are in MeV). The last two columns show the relative errors of cases I and II in comparison to experimental data.

Baryon	CaseI	CaseII	Exp.	Ref. [11]	Ref. [23]	Ref. [25]	Ref. [26]	Error I	Error II
\sum_c^{++}	2454	2459	2454	2318	2452	2454	2425	0.0%	0.2%
\sum_c^{++*}	2492	2508	2518	2446	2581	2526	2488	1.0%	0.4%
\sum_c^0	2459	2461	2453	2323	2457	2458	2442	0.2%	0.3%
\sum_c^{0*}	2497	2510	2518	2451	2586	2530	2507	0.8%	0.3%
$\sum_c^{\bar{0}}$	2464	2462	2454	2328	2461	2460	2460	0.4%	0.3%
$\sum_c^{\bar{0}*}$	2503	2512	2518	2456	2591	2533	2526	0.6%	0.2%
Ξ_c^+	2576	2504	2468	2467	2466	2545	2512	4.4%	1.5%
Ξ_c^{+*}	2634	2583	2647	2577	2596	2614	2584	0.5%	2.4%
Ξ_c^0	2581	2506	2471	2453	Input	2547	2529	4.5%	1.4%
Ξ_c^{0*}	2639	2585	2646	2582	2601	2616	2604	0.3%	2.3%
Ω_c^0	2715	2566	2697	2587	2476	2631	2601	0.7%	4.9%
Ω_c^{0*}	2773	2648	2768	2716	2606	2700	2684	0.2%	4.3%

Table 4. Single beauty baryon masses (masses are in MeV). The last two columns show the relative errors of cases I and II in comparison to experimental data.

Baryon	caseI	caseII	Exp.	Ref. [11]	Ref. [23]	Ref. [25]	Ref. [26]	Error I	Error II
\sum_b^+	5834	5808	5807	5700	Input	5816	5772	0.5%	0.0%
\sum_b^{+*}	5872	5858	5829	5826	5936	5888	5793	0.7%	0.5%
\sum_b^0	5839	5810	5811	-	-	5819	5793	0.5%	0.0%
\sum_b^{0*}	5877	5860	5832	-	-	5890	5816	0.8%	0.5%
\sum_b^-	5844	5811	5815	5708	5818	5821	5816	0.4%	0.1%
\sum_b^{-*}	5882	5861	5836	5836	5946	5892	5840	0.8%	0.4%
Ξ_b^0	5956	5848	5787	5828	5821	5886	5880	2.9%	1.1%
Ξ_b^{0*}	6014	5928	-	5957	5956	5972	5907	-	-
Ξ_b^-	5961	5849	5792	5833	5826	5887	5903	2.9%	1.0%
Ξ_b^{-*}	6019	5930	-	5962	5956	5974	5931	-	-
Ω_b^-	6095	5903	6054	5967	-	5986	5994	0.7%	2.5%
Ω_b^{-*}	6135	5986	-	6096	5961	6049	6028	-	-

we see that the results of the present work are in good agreement with experimental data and other predictions. A comparison between the results of case I and the previous work [11] shows that the results obtained in case I are closer to experimental data. Note that the results of case II are very close to the ones obtained by Refs. [23, 25].

By comparing the results of cases I and II, we find that, apart from the Ω_c and Ω_b baryons, the results obtained in case II are overall closer to experimental data and other predictions than the ones obtained in case I and also in previous works. Also Tables 6-8 show that the predicted masses of double and triple heavy-flavor baryons in case II are closer to the results of other works.

6 Summary

In this paper we have studied masses and magnetic moments of heavy-flavor baryons containing one, two, and three heavy-flavor quarks in the ground-state ($\gamma = 0$) for the different confining potentials (1) and (2). Using the hypercentral approach we have simplified the three-body problem and solved the Schrödinger equation numerically to obtain the ground-state energy eigenvalues and eigenfunctions

Table 5. Magnetic moments of single charm and single beauty baryons with $J^P = 3/2^+$ in terms of the nuclear magneton μ_N .

Baryon	caseI	caseII	Ref. [9]	Ref. [25]	Ref. [28]	Ref. [29]
Σ_c^{++*}	4.10	3.766	3.842	3.739	3.407	3.560
Σ_c^{+*}	1.32	1.220	1.252	1.210	1.130	1.170
Σ_c^{0*}	-1.44	-1.333	-0.848	-1.322	-1.146	-1.230
Ξ_c^{+*}	1.04	1.503	1.513	1.485	1.264	1.430
Ξ_c^{0*}	-1.18	-1.124	-0.688	-1.111	-0.986	-1.000
Ω_c^{0*}	-0.92	-0.903	-0.865	-0.887	-0.833	-0.770
Σ_b^{+*}	3.69	3.588	3.234	3.570	3.082	-
Σ_b^{0*}	0.89	0.865	0.791	0.861	0.724	-
Σ_b^{-*}	-1.91	-1.859	-1.655	-1.849	-1.634	-
Ξ_b^{+*}	1.157	1.136	1.041	1.127	0.875	-
Ξ_b^{0*}	-1.65	-1.621	-1.095	-1.609	-1.477	-
Ω_b^{0*}	-1.38	-1.380	-1.199	-1.365	-1.292	-

Table 6. Double and triple charm baryon masses (in MeV).

Baryon	caseI	caseII	Ref. [11]	Ref. [23]	Ref. [30]	Ref. [29]
$\Xi_{cc}^{++}(ucc)$	3703	3532	3579	3583	3510	3676
$\Xi_{cc}^{+*}(ucc)$	3765	3623	3708	3722	3548	3753
$\Omega_{cc}^{+}(scc)$	3846	3667	3718	3592	3719	3815
$\Omega_{cc}^{+*}(scc)$	3904	3758	3847	3731	3746	3876
$\Omega_{ccc}^{+++}(ccc)$	5035	4880	4978	4842	4803	4965

Table 7. Double and triple charm baryon masses (in MeV).

Baryon	caseI	caseII	Ref. [11]	Ref. [23]	Ref. [30]	Ref. [29]
$\Xi_{bb}^0(ubb)$	10467	10334	10339	10284	10130	10340
$\Xi_{bb}^{0*}(ubb)$	10525	10431	10468	10427	10144	10367
$\Omega_{bb}^-(sbb)$	10606	10397	10478	10293	10422	10454
$\Omega_{bb}^{-*}(sbb)$	10664	10495	10607	10436	10432	10486
$\Omega_{bbb}^{-*}(bbb)$	15175	15023	15118	14810	14569	14834

Table 8. Beauty and charm baryon masses (in MeV).

Baryon	caseI	caseII	Ref[11]	Ref. [23]	Ref. [27]	Ref. [30]
$\Omega_{cb}^+(ucb)$	7087	6988	6959	6935	6928	6792
$\Omega_{cb}^{+*}(ucb)$	7145	7083	-	7076	-	6827
$\Omega_{cb}^0(scb)$	7226	7103	7098	6945	7013	6999
$\Omega_{cb}^{0*}(scb)$	7284	7200	-	7085	-	7024
$\Omega_{ccb}^+(ccb)$	8357	8190	8229	8038	-	8018
$\Omega_{ccb}^{+*}(ccb)$	8415	8290	8358	8186	-	8025
$\Omega_{cbb}^0(cbb)$	11737	11542	11609	11363	-	11280
$\Omega_{cbb}^{0*}(cbb)$	11795	11643	11738	11512	-	11287

of baryonic systems. Hyperfine spin- and isospin-dependent interactions result in small shifts of the baryon energy. Our results are similar to those of other works. The confining interaction including a harmonic-oscillator term seems to give results closer to experimental data, especially for double and triple heavy baryons. Our approach can also be used to study other three-body systems in the fields of nuclear, atomic, and molecular physics.

References

- [1] C. Albertus, E. Hernandez, J. Nieves and J. M. Verde-Velasco, Eur. Phys. J. A **32** (2007) 183 [Erratum-ibid. A **36** (2008) 119]
- [2] D. Ebert, R. N. Faustov, V. O. Galkin and A. P. Martynenko, Phys. Rev. D **66** (2002) 014008
- [3] J. -R. Zhang and M. -Q. Huang, Phys. Rev. D **78** (2008) 094015
- [4] X. H. Guo and T. Muta, Mod. Phys. Lett. A **11** (1996) 1523
- [5] D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **72** (2005) 034026
- [6] C. Albertus, J. E. Amaro, E. Hernandez and J. Nieves, Nucl. Phys. A **755** (2005) 439
- [7] J. M. Flynn *et al.* [UKQCD Collaboration], JHEP **0307** (2003) 066
- [8] A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, D. Nicmorus and K. Pumsa-ard, Phys. Rev. D **73** (2006) 094013
- [9] B. Patel, A. K. Rai and P. C. Vinodkumar, J. Phys. G **35** (2008) 065001 [J. Phys. Conf. Ser. **110** (2008) 122010]
- [10] B. Patel, A. Majethiya and P. C. Vinodkumar, Pramana **72** (2009) 679
- [11] Z. Ghalenovi, A. A. Rajabi and M. Hamzavi, Acta Phys. Polon. B **42** (2011) 1849
- [12] N. Isgur and G. Karl, Phys. Rev. D **18** (1978) 4187
- [13] S. Capstick and N. Isgur, Phys. Rev. D **34** (1986) 2809
- [14] M. M. Giannini, Rept. Prog. Phys. **54** (1990) 453
- [15] L. Y. Glozman and D. O. Riska, Phys. Rept. **268** (1996) 263
- [16] N. Salehi, A. A. Rajabi and Z. Ghalenovi, Acta Phys. Polon. B **42** (2011) 1247
- [17] H. Hassanabadi, A. A. Rajabi and S. Zarrinkamar, Mod. Phys. Lett. A **23** (2008) 527
- [18] H. Hassanabadi and A. A. Rajabi, Few-Body Syst. **41** (2005) 201
- [19] A. A. Rajabi, Few-Body Syst. **37** (2005) 4
- [20] G. S. Bali *et al.* [TXL and T(X)L Collaborations], Phys. Rev. D **62** (2000) 054503
- [21] G. Plante and A. F. Antippa, J. Math. Phys. **46** (2005) 062108
- [22] M. M. Giannini, E. Santopinto and A. Vassallo, Prog. Part. Nucl. Phys. **50** (2003) 263
- [23] Z. Ghalenovi, A. A. Rajabi and A. Tavakolinezhad, Int. J. Mod. Phys. E **21** (2012) 1250057
- [24] B. Patel, A. Majethiya and P. C. Vinodkumar, Phys. At. Nucl. **65** (2002) 917
- [25] Z. Ghalenovi and A. Akbar Rajabi, Eur. Phys. J. Plus **127** (2012) 141

- [26] B. Patel, A. K. Rai and P. C. Vinodkumar, *Pramana* **70** (2008) 797
- [27] C. Albertus, E. Hernandez and J. Nieves, *Phys. Lett. B* **683** (2010) 21
- [28] A. Majethiya, B. Patel and P. C. Vinodkumar, *Eur. Phys. J. A* **38** (2008) 307
- [29] W. Roberts and M. Pervin, *Int. J. Mod. Phys. A* **23** (2008) 2817
- [30] A. P. Martynenko, *Phys. Lett. B* **663** (2008) 317
- [31] W. M. Yao *et al.* [Particle Data Group Collaboration], *J. Phys. G* **33** (2006) 1
- [32] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **99** (2007) 202001
- [33] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **99** (2007) 052002
- [34] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. D* **80** (2009) 072003
- [35] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **107** (2011) 102001